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**EFFECTS OF ELECTRIC FIELDS AND CURRENTS ON
MICROSTRUCTURE, PROPERTIES AND PROCESSING OF
METALS AND ALLOYS**

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Summary of Research at North Carolina State University

Technical Report

Hans Conrad and Arnold F. Sprecher

July 1, 1990

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Materials Science and Engineering Department
North Carolina State University
Raleigh, NC 27695-7907

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13. ABSTRACT (Maximum 200 words) This report presents a summary of the results obtained by the authors and coworkers at North Carolina State University (NCSU) during the past 10 years on the effects of electric fields and currents on the properties and processing of metals and alloys. These results confirm that an electric field or current can have a <u>significant direct</u> influence on the microstructure and properties of metals and alloys, in addition to the indirect effects of Joule heating or induced mechanical stresses. The resulting effects thus need to be taken into account when considering the use of metals and alloys (structural or electronic) in environments containing such fields or currents. Moreover, the effects can be beneficial in the working, forming and processing of metals and alloys, offering opportunities regarding: (a) difficult-to-fabricate materials, (b) more efficient processes, (c) manipulation of microstructure and (d) improved properties of the product. Included at the end of the research summary is a list of the publications resulting from the work at NCSU and the announcements pertaining to the research, including coverage by CNN-TV and by the technical news media.				
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Effects of Electric Fields and Currents on Microstructure, Properties and Processing of Metals and Alloys

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Summary of Research at North Carolina State University

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SUMMARY OF RESEARCH AT NORTH CAROLINA STATE UNIVERSITY

Effects of Electric Fields and Currents on Microstructure, Properties and Processing of Metals and Alloys

1. INTRODUCTION

This report presents a summary of the results obtained by the authors and coworkers at North Carolina State University (NCSU) during the past 10 years on the effects of electric fields and currents on the properties and processing of metals and alloys. These results confirm that an electric field or current can have a significant direct influence on the microstructure and properties of metals and alloys, in addition to the indirect effects of Joule heating or induced mechanical stresses. The resulting effects thus need to be taken into account when considering the use of metals and alloys (structural or electronic) in environments containing such fields or currents. Moreover, the effects can be beneficial in the working, forming and processing of metals and alloys, offering opportunities regarding: (a) difficult-to-fabricate materials, (b) more efficient processes, (c) manipulation of microstructure and (d) improved properties of the product. Included at the end of the research summary is a list of the publications resulting from the work at NCSU and the announcements pertaining to the research, including coverage by CNN-TV and by the technical news media.

We would be most pleased to enter into a contractual arrangement (or research grant) to explore the application of the various observed effects and phenomena due to electric fields and currents to your specific interests, processes or products.

2. ELECTROPLASTICITY

2.1 Effects of High Density Electric Current Pulses

2.1.1 Phenomenological Equation: The procedure employed in our studies on the effects of high density ($10^3 - 10^6$ A/cm²) electric current pulses ($\sim 100\mu$ s duration) on the plastic flow of metals (term $\dot{\epsilon}_j$ the electroplastic effect) and the phenomenological (constitutive) equations which apply are presented in Fig. 1. The procedure employed is illustrated in Fig. 1a [1-3,7], whereby a current pulse is applied during plastic flow in uniaxial tension at a constant strain rate giving the stress drop $\Delta\sigma_f$ and also applied in the elastic regime giving $\Delta\sigma_E$. The latter stress drop results from the side effects of the current pulse, e.g. Joule heating and electro-magnetic forces. The increase in plastic strain rate resulting from the electric current pulse $\dot{\epsilon}_j$ is then taken to be

$$\dot{\epsilon}_j = (\Delta\sigma_f - \Delta\sigma_E) / E_m t_p \quad (1)$$

where E_m is the system (machine plus specimen) modulus and t_p is the pulse duration time.

Fig. 1b [4] gives a log-log plot of the ratio $\dot{\epsilon}_j$ to the plastic strain rate prior to the application of the current pulse $\dot{\epsilon}_{j=0}$ ($\equiv \dot{\epsilon}_a$) giving

$$\dot{\epsilon}_j / \dot{\epsilon}_a = (j/j_c)^n \quad (2)$$

where j is the current density and $n = 2.5 - 3.0$. Worthy of note is that a significant effect of the current only occurs for a critical current density $j_c > 10^3 - 10^4 \text{ A/cm}^2$. Also to be noted is that reasonable agreement of the results on Zn single crystals exists for constant strain rate (flow stress tests with a single pulse) and for creep and stress relaxation tests with multipulsing (e.g. 100 pulses per s).

Fig 1c presents a log-log plot of j_c vs the free electron concentration n_e represented by the various metals considered [4,9]. The results suggest an equation of the form

$$j_c = a n_e^m \quad (3)$$

where m has a value of $\sim 2/3$ at 300 K and $\sim 2/5$ at 77K.

2.1.2 Mechanisms: Studies into the mechanisms responsible for the electroplastic effect are summarized in Fig. 2. The magnitude of $\dot{\epsilon}_j$ was generally of the order of 10^{-1} to 10^1 s^{-1} , which is in the range where thermally activated plastic flow is expected to occur. The application of the concept of thermally activated dislocation motion to electroplasticity is illustrated in Fig. 2a[2-4]. This gives

$$\dot{\epsilon}_j / \dot{\epsilon}_a = (\dot{\epsilon}_{oj} / \dot{\epsilon}_o) \exp - (\delta\Delta H^* / kT) \exp(V^* \sigma_{ew} / kT) \quad (4)$$

where $\dot{\epsilon}_{oj}$ is the pre-exponential factor for the current pulse, $\dot{\epsilon}_o$ that without, $\delta\Delta H^*$ the change in activation enthalpy due to the current, V^* the activation volume and σ_{ew} the electron wind stress. Fig. 2b shows the relative contribution of the various factors in Eqn. 4 to the increased plastic strain rate resulting from a current pulse [8,9]. It is here seen that the greatest effect of the current pulse on the increase in plastic strain rate is through the pre-exponential factor, smaller effects occurring through the activation enthalpy and the electron wind stress. The reason that $\delta\Delta H^*$ (where $\Delta H^* = \Delta U^* - V^* \sigma^*$) makes a significantly smaller contribution to the increased strain rate is that even though the current produces a large reduction in the energy ΔU^* , it also gives a decrease in the activation volume V^* and in turn the work done ($= V^* \sigma^*$) by the applied stress σ^* during thermal activation.

The magnitude of the electron wind force F_{ew} derived from experimental measurements is compared with theoretical predictions in Fig. 2c through the electron wind push coefficient B_{ew} acting on dislocations [4,9], which is given by

$$B_{ew} = F_{ew}/v_e = (\sigma_{ew}b/M)/(j/en_e) \quad (5)$$

v_e is the electron drift velocity, b the Burgers vector, M the Taylor orientation factor relating the tensile stress on polycrystals to the resolved shear stress, e the charge on the electron and n_e the free electron density. It is seen in Fig. 2c that B_{ew} for the FCC metals Cu, Ag and Al is in reasonable accord with theoretical predictions, but that for the BCC transition metal Nb is about an order of magnitude higher.

2.2. Effects of an External Electric Field

2.2.1 Superplastic Deformation

2.2.1.1 Mechanical Properties: The experimental set-up employed to determine the effects of an external DC electric field on the superplastic deformation of 7475 Al alloy is shown in Fig. 3a. An electric field of the order of 2kV/cm produced a decrease in the flow stress (Fig. 3b), a slight increase in the strain rate hardening exponent $m = d \log \sigma / d \log \dot{\epsilon}$ (Fig 3c) and a significant decrease in the strain hardening coefficient $\Theta = d\sigma/d\epsilon$ (Fig. 3d) [11-14]. The influence of polarity and magnitude of the electric field on the maximum flow stress σ_{max} is shown in Fig. 3c, where it is seen that a decrease in σ_{max} occurs when the specimen is connected to the positive terminal of the power supply and an increase when it is connected to the negative terminal [13]. In addition to the effects shown in Fig. 3, an electric field was found to reduce the activation energy for superplastic deformation [13].

2.2.1.2 Microstructure: Fig. 4 presents the effects of an electric field on the microstructure which develops during the superplastic deformation of the 7475Al alloy [8, 27-29]. In Fig. 4a, the influence of the field on cavitation is shown. Evident is that the field significantly reduces the volume fraction of cavities at all levels of plastic strain ϵ_p . Moreover, the reduction in cavities becomes greater with increase in the field strength for both polarities of the specimen. However, the effect of the field is larger when the specimen is connected to the positive terminal compared to the negative terminal of the power supply. Fig. 4b shows that the field also retards grain growth during superplastic deformation and the table of Fig. 4c illustrates that the field influences the composition of the dispersoid-free zone (DFZ) which develops adjacent to the grain boundaries during superplastic deformation.

In addition to the above-mentioned effects of an electric field on microstructure during the superplastic deformation of the 7475Al alloy, the field produced a decrease in dislocation density in the DFZ and a reduction in the size of the dispersoid particles adjacent to the DFZ [28]. The observed changes in microstructure suggest that the electric field influences diffusion, i.e. the concentration and/or migration rate of vacancies.

3. Electroprocessing

3.1 Annealing

3.1.1 Effects of High Density Electric Current Pulses

The effect of high density electric current pulses (2 per s) on the annealing response of two purities of cold worked Cu is shown in Fig. 5a [15-2]. Evident is that the current pulsing significantly enhanced the rates of recovery and recrystallization, even though the current

was being "on" only $\sim 10^{-4}$ fraction of the total time of anneal. An increase in impurity content from -0.01 to 0.01 wt. % reduced the effect on recovery, but had no appreciable influence on recrystallization as given by the reduction in temperature for a 50% drop in hardness ΔT_{50} . The effects of electropulsing decreased with increase in amount of prior cold works [16]. Results similar to those for Cu were also obtained for the annealing of cold worked Al [21]. Fig. 5b shows that electropulsing also enhances the rates of recovery and recrystallization of the intermetallic compound Ni_3Al [19].

Studies into the effects of electropulsing on the recrystallization kinetics of Cu revealed that the electropulsing mainly increased the pre-exponential factor of the Arrhenius rate equation having only little if any influence on the activation energy [17,18]. It is proposed that the influence of electropulsing on recovery and recrystallization is through its effect on vacancy concentration and/or flux, which in turn affect the rates of dislocation climb involved in recovery and of subgrain formation and coalescence involved in the nucleation of new grains during recrystallization [18,19,21].

Although electropulsing enhances the rates of recovery and recrystallization, it retards the rate of grain growth in the temperature regime immediately following recrystallization [18-21]; see Fig. 5c. The degree of retardation of grain growth increased with increase in pulse frequency in the range of 0.07 to 7 Hz, but was relatively independent of pulse duration time in the range of 50 to 200 μs , Fig. 5d [20]. It is concluded that the influence of electropulsing on the rate of grain growth results from an increased rate of annihilation of residual dislocations in the newly recrystallized grains.

In addition to enhancing the rates of recovery and recrystallization and retarding grain growth, electropulsing produced a finer recrystallized grain size (with somewhat more irregular shaped grains) and a sharper texture [15,18].

3.1.2 Effects of an External Electric Field

The experimental arrangement used in studies on the influence of an external electric field on the annealing of metals and alloys is shown in Fig. 6a. The effect of an external electric field of the order of a kV/cm on the isochronal annealing behavior of Cu is presented in Fig. 6b [25]. It is here seen that the field retards the rates of recovery and recrystallization, the degree of retardation increasing with increase in amount of prior cold work. Moreover, a polarity effect occurs in that the field only has an influence when the specimen is connected to the positive terminal of the power supply. However, the effect is not sensitive to the dielectric medium between the specimen from the companion electrode.

The influence of an external electric field on the isochronal annealing response of the intermetallic compound Ni_3Al is shown in Fig. 6c [19]. It is here seen that the field enhances the rates of recovery and recrystallization for this alloy and is independent of polarity, both being in contrast to that found for Cu. Fig. 6d compares the effects of an electric field $E = 1.9 \text{ kV/cm}$ and electropulsing ($j = 4.6 \times 10^4 \text{ A/cm}^2$, $t_p = 100 \mu\text{s}$, $v_p = 2 \text{ Hz}$) on the relative change in hardness of the Ni_3Al during isochronal annealing [19]. Evident is that the largest effects of the field and electropulsing occur during the early stages of the recrystallization process, i.e. when the hardness decrease is about 10-40% of the total drop in hardness which results upon annealing at 1000°C . The mechanism(s) by which an electric field influences recovery and recrystallization is not clear at this time. It appears that the field affects the concentration and/or flux of vacancies, which in turn govern dislocation climb and subgrain formation and coalescence.

3.2 Solid State Phase Transformations

3.2.1 Effects of High Density Electric Current Pulses

3.2.1.1 Crystallization of Amorphous Alloys: Electropulsing was found to enhance the rate of crystallization of amorphous iron-base alloys [22].

3.2.1.2 Tempering of Steel: The rate of tempering of an O2 tool steel was slightly enhanced by electropulsing [unpublished research NCSU, 1989].

3.2.2 Effects of an External Electric Field

3.2.2.1 Quench Aging in Iron: An electric field retarded the rate of quench aging in iron [23].

3.2.2.2 Hardenability of Steel: The experimental arrangement used in studies into the effects of an external electric field on the hardenability of steels is illustrated in Fig. 7a [30]. Because the rod to which the specimen is attached acts as a heat source, the arrangement simulates a Jominy end-quench. This is illustrated in Fig. 6b, where it is seen that upon quenching an O2 tool steel in silicone oil at 25°C the electric field produces a hardness at the specimen tip away from the holding rod which is essentially equal to that for quenching in water without a field, but which drops off with distance towards the end attached to the holding rod. The hardness at the tip obtained with the field for the silicone oil quench is about twice that without a field [30]. The microstructure at the specimen tip obtained for the silicone oil quench was martensite with the field and pearlite without, in keeping with the hardness values.

The results presented in Fig. 7b show that the influence of the field varies with the quenching rate, being greatest at an intermediate quench rate [30]. These effects of the field are interpreted in terms of the CT diagram in Fig. 7d. It is concluded that the electric field shifts the CT diagram to longer times, i.e. it retards the rate of transformation of austenite to bainite or pearlite, thereby permitting a slower cooling rate to obtain martensite.

3.2.2.3 Tempering of Steel: An electric field retarded slightly the rate of tempering of an O2 tool steel [23].

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EFFECTS OF ELECTRIC FIELDS AND CURRENTS ON MICROSTRUCTURE, PROPERTIES AND PROCESSING OF METALS AND ALLOYS

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EFFECTS OF ELECTRIC FIELDS AND CURRENTS ON MICROSTRUCTURE, PROPERTIES AND PROCESSING OF METALS AND ALLOYS

Media Coverage

I. National and International Television

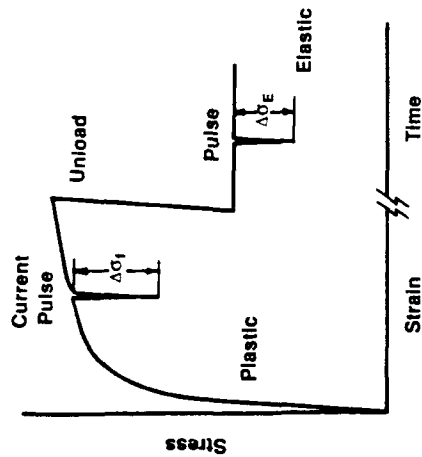
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Fig.1 Effect of High-Density Electric Current Pulses on the Plastic Deformation of Metals: Phenomenological

a. Experimental



$$\dot{\epsilon}_j = (\Delta\sigma_f - \Delta\sigma_E) / E_M t_p$$

σ = stress

ϵ = strain

$\dot{\epsilon}_a$ = applied strain rate

$\Delta\sigma_f$ = drop in flow stress in plastic deformation range

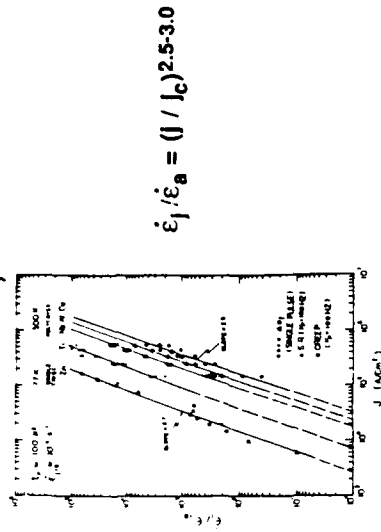
$\Delta\sigma_E$ = drop in flow stress in elastic deformation range

t_p = pulse duration

E_M = system modulus

$\dot{\epsilon}_j$ = Increase in Strain Rate from Current Pulse

b. Effect of Current Density j on Plastic Strain Rate $\dot{\epsilon}_j$



c. Effect of Conduction Electron Density n_e on Critical Current Density j_c

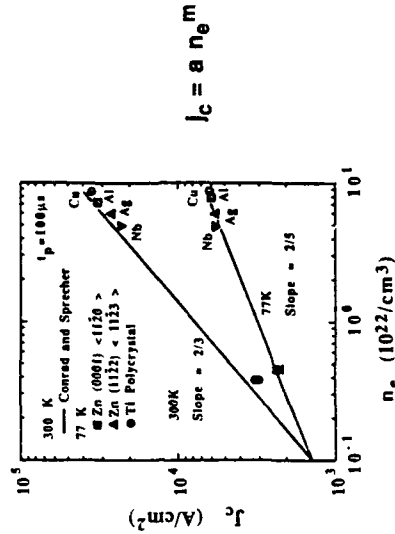
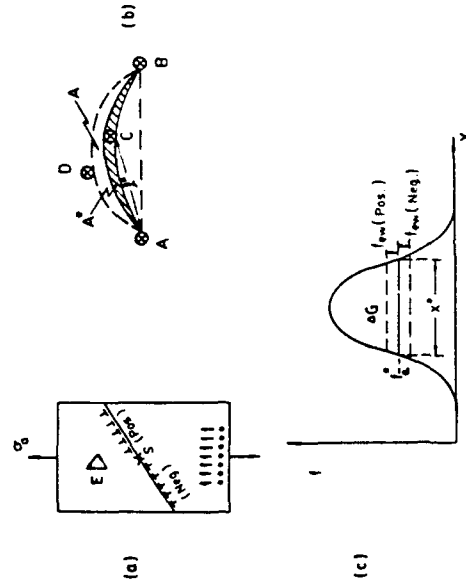


Fig.2 Effect of High-Density Electric Current Pulses on the Plastic Deformation of Metals: Mechanisms

a. Thermally Activated Deformation Approach



$$\dot{\epsilon}_1 / \dot{\epsilon}_a = (\dot{\epsilon}_0 / \dot{\epsilon}_0) e^{-\delta \Delta H^* / kT} e^{V^* \sigma_{ew} / kT}$$

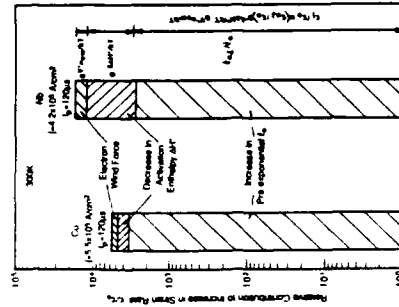
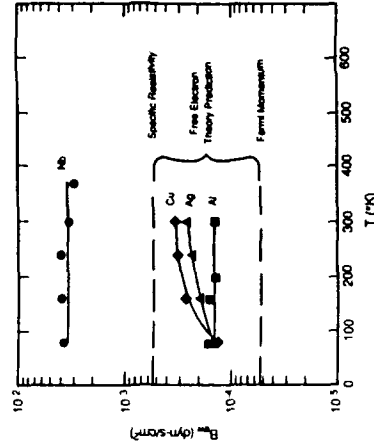
$$\Delta G = \Delta H^* - T \Delta S^*$$

$$\dot{\epsilon}_0 = \text{Pre-exponential}$$

$$V^* = \text{Activation Volume}$$

$$\sigma_{ew} = \text{Electron Wind Stress}$$

b. Relative Contribution to Increased Strain Rate

c. Electron Wind Push Coefficient B_{ew} 

$$F_{ew} = \text{Electron Wind Force}$$

$$v_e = \text{Electron Drift Velocity}$$

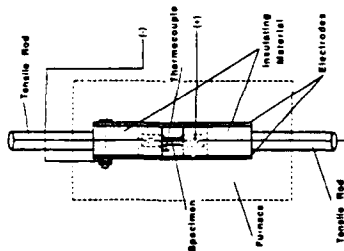
$$e = \text{Electron Charge}$$

$$B_{ew} = F_{ew} / v_e = (\sigma_{ew} b / \bar{M} k e n_e / l)$$

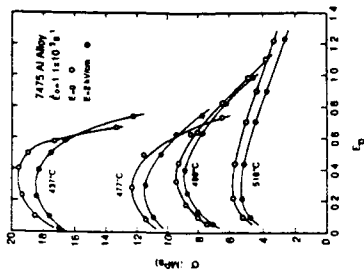
Electroplasticity

Fig.3 Effect of An Electric Field on Superplastic Deformation of 7475 Al

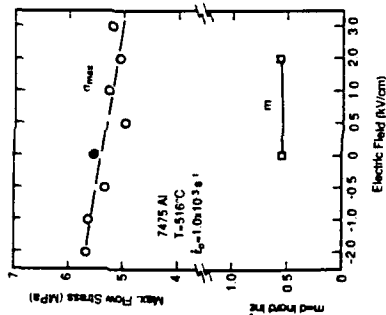
a. Experimental Set-Up



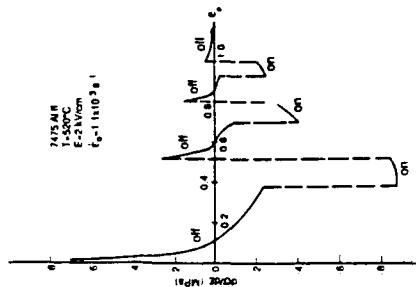
b. Effect of Electric Field on Stress-Strain Curve



c. Effect of Electric Field on σ_{max} and on Strain Rate Hardening Exponent



d. Effect of Electric Field Cycling on Strain Hardening



Electroplasticity

Effect of DC Electric Field on Microstructure during Superplastic Deformation of 7475 Al Sheet (1.2mm)

a. Cavitation

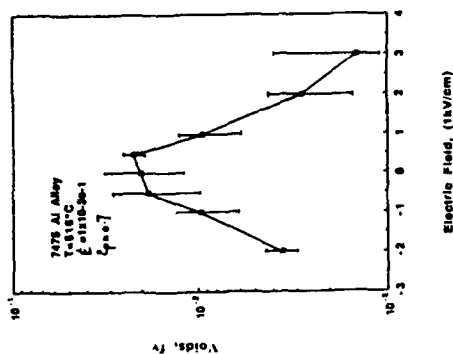
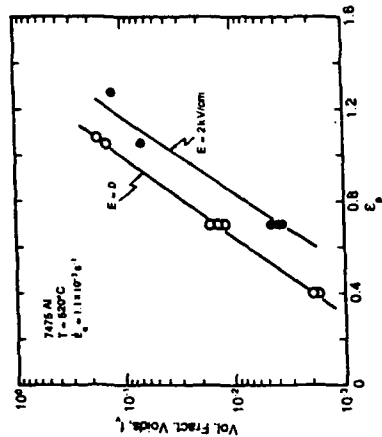


E=0

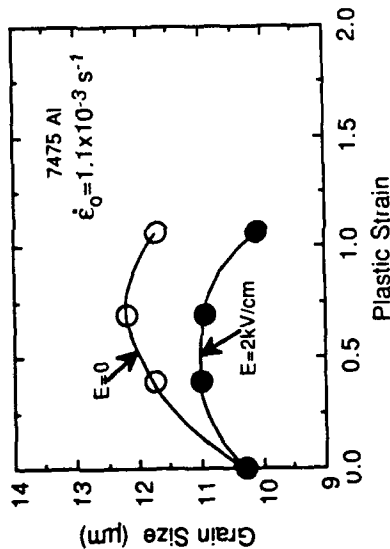
10 μm

E=2kV/cm

10 μm



b. Grain Size

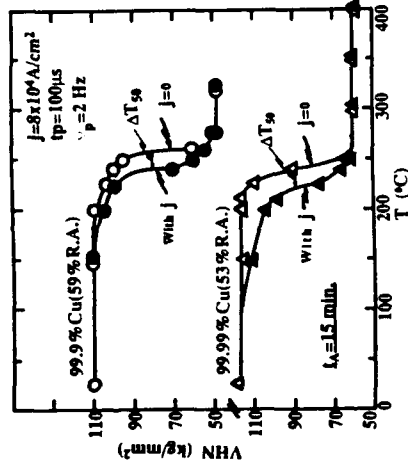


c. Chemical Composition: EDS Analysis of Dispersoid-Free Zone

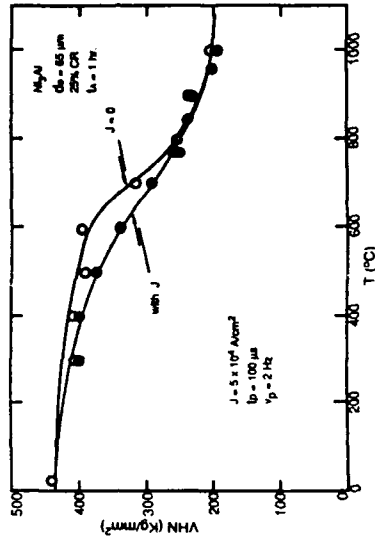
E (kV/cm)	Location	I(Zn)/I(Cu)
0	Matrix	1.8
0	DFZ	1.7
2	Matrix	1.7
2	DFZ	3.0

Fig.5 Effect of High Density Electric Current Pulses on the Annealing Response of Metals and the Intermetallic Ni_3Al

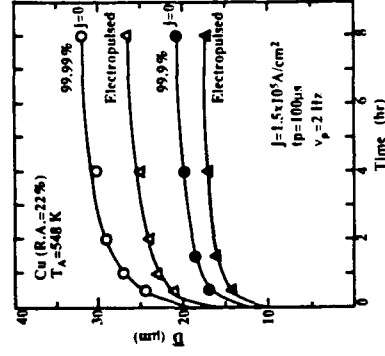
a. Isochronal Anneal of Cu



b. Isochronal Anneal of Ni_3Al



c. Grain Growth in Cu



d. Effects of Pulse Duration and Frequency on Grain Growth in Cu

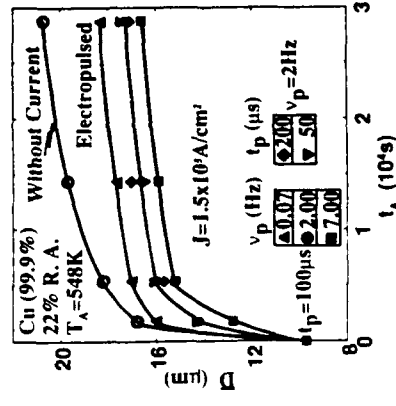
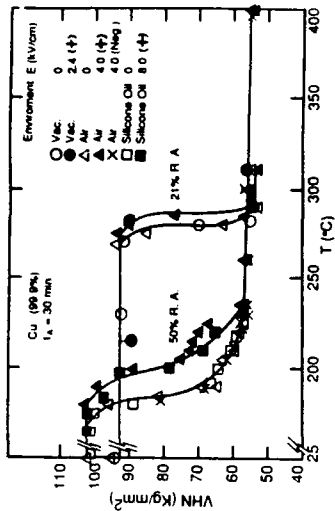


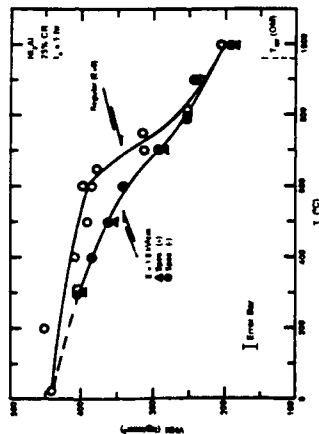
Fig.6 Effect of an Electric Field on the Annealing Response of Metals and the Intermetallic Ni_3Al

b. Effect of Electric Field on Annealing of Cu. Note Polarity Effect

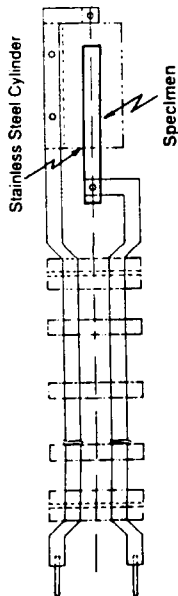
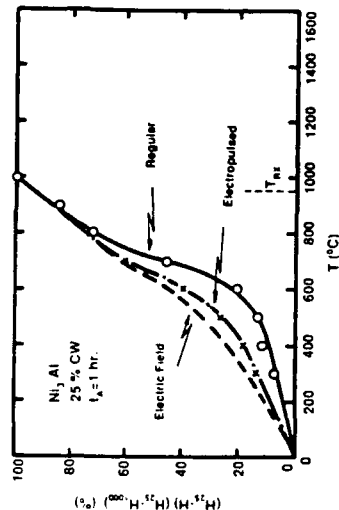
a. Experimental



c. Effect of Electric Field on Annealing of Ni_3Al . No Polarity Effect



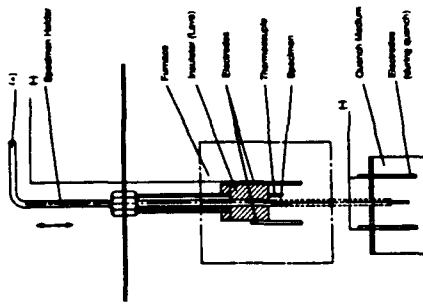
d. Comparison of the Effect of Electric Field with Electropulsing on the Relative Change in Hardness of Ni_3Al vs Annealing Temperature



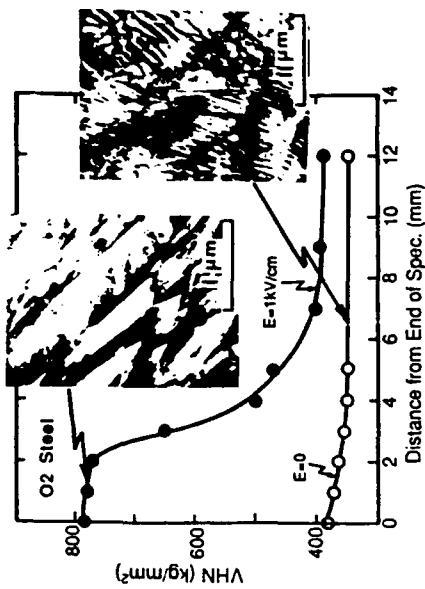
Electro-Processing

Fig.7 Effect of DC Electric Field on the Hardenability of Steel
(3mm dia. Specimen)

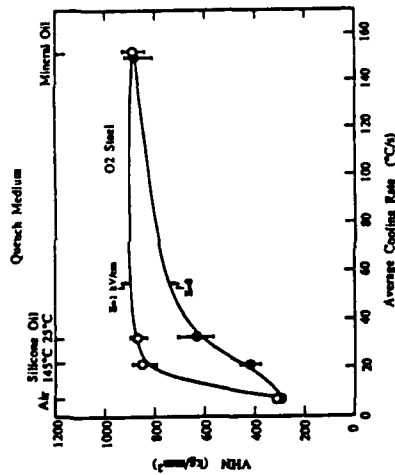
a. Experimental Set-Up



b. Simulated Jominy End-Quench



c. Effect of Cooling Rate



d. Explanation: Shift of CT Diagram

